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Ground heat transfer effects on the thermal performance of earth-contact structures

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Abstract

A review of ground heat transfer effects on the thermal performance of earth contact structures is presented. The fundamental heat transfer processes relevant to the problem are described along with methods of determining thermal properties of soils. An overview of the many analytical, semi-analytical and numerical methods available to solve the heat transfer problem is also provided, followed by a brief summary of design guides.

The review also considers the influence of changes in ground water content on the heat transfer properties of soils. A description of the processes that give rise to changes in ground water conditions is provided. The bulk thermal conductivity of a soil is shown to be strongly related to its water content. An overview of methods of analysing changes in soil moisture content is then presented. Methods of estimating the relevant hydraulic properties of soils are also considered. The final part of the review provides a brief outline of the theoretical approach required to analyse coupled heat and moisture migration in soils.

Notwithstanding the fact that there are many practical design tools available, it appears that further work is necessary to clarify the circumstances in which more sophisticated analysis is warranted. Recent studies indicate that geometric simplification can lead to quite significant errors in heat loss calculation. Full three-dimensional treatment appears to be necessary in some cases.

Thermal properties of soils vary according to the properties and proportions of the

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constituent phases (air/water/solid). Soil moisture content variations occur naturally or as a result of anthropogenic activity. The influence of such variations on the thermal conductivity of the ground is significant. The review outlines some simplified methods of accommodating this feature of the ground heat transfer problem. However, this aspect of the problem appears to need further consideration.

Nomenclature

A_f, A_w	area — floor, wall, etc.
A	constant in Eq. (51)
a, b, c	constants
B_i	coefficients in Eq. (24)
B'	characteristic dimension of floor
c_{salt}	concentration of salt
CDD	cooling degree days
c	heat capacity
c_i	specific heat capacity of phase i
$C_{\psi\psi}$, $C_{\psi T}$	moisture storage coefficients in Eq. (61)
$C_{T\psi}$, C_{TT}	heat storage coefficient in Eq. (62)
C_s	shape coefficient
D_{atm}	molecular diffusivity of water vapour in air
D_{Tliq}	thermal liquid diffusivity
$D_{\theta liq}$	isothermal liquid diffusivity
D_θ	moisture diffusivity
e	void ratio
erfc	error function
F_2	heat loss coefficient
F_d	decrement factor
g	gravitational constant
g_a	defined in Eq. (21)
HDD	heating degree days
k	intrinsic permeability
k_i	temperature gradient across solids, Eq. (17)
k_{rl}	relative liquid phase coefficient of permeability
k_s	hydraulic conductivity of saturated soil
k_l	hydraulic conductivity of unsaturated soil
K_s	coupling coefficient in Eq. (31)
L	length
L_0	latent heat of vaporisation, Eqs. (60) and (62)
L_s	thickness of solid layer
L_a	thickness of air layer
m	moisture content by weight
n_{salt}	number of molecules per mole of salt in Eq. (39)

n	constant
P	perimeter of the exposed edge of floor
q_{cond}	conductive heat flux
q_{conv}	convective heat flux
q_{h}	heat flux
q_{lat}	heat flux due to latent heat
q_{lconv}	heat flux generated by liquid convection
q_{vconv}	heat flux generated by vapour convection
Q	heat flux
Q_{a}	annual amplitude
Q_m	mean annual heat loss
Q_{nt}	heat loss in zone at time t
$Q_{m,n}$	mean annual heat loss at zone n
$Q_{\mathrm{A},n,t}$	annual amplitude of the heat loss in zone n
Q_{R}	rate of heat generation
Q_z	heat flux
$r_1, r_2, \ldots, r_n$	mean radius of the pores in different pore classes
R	thermal resistance
R_{g}	universal gas constant, Eq. (39)
R_{w}	thermal resistance of wall
R_{ins}	thermal resistance of insulation
S_0	wetter surface per unit volume of particles
S_{a}	degree of saturation of pore air
S_{e}	effective degree of saturation
S_{l}	degree of saturation
S_{w}	degree of saturation of pore water
S_{wu}	residual degree of saturation
t	time
T	temperature
T_{o}	reference or outdoor temperature
T_{i}	inside temperature
T_{s}	ground surface temperature
T_{R}	mean temperature of slab
T_z	monthly average subfloor temperature at a given depth
u_{a}	pore air pressure
u_{w}	pore water pressure
U	U-value
U_0	thermal transmittance of slab-on-grade floor
U_{f}	U-value of floor
U_{w}	U-value of wall
$\bar{v}_{\mathrm{l}}$	velocity of liquid
$\bar{v}_{\mathrm{v}}$	velocity of vapour
x, y, z	spatial co-ordinates

Greek symbols

α	constant in Eq. (51)
α_l	constant in Eq. (51)
γ_l	density of liquid
γ_p	unit weight of the permeant
δ	constant
ϵ	phase conversion factor
η	soil porosity
θ	volumetric moisture content
θ_s	saturated volumetric water content
θ_l	volumetric liquid content
θ_v	volumetric vapour content
λ	thermal conductivity
λ_i	thermal conductivity of phase i
μ	dynamic viscosity
Π	notation for product of multiplication
ρ	density
ρ_i	density of phase i
ρ_d	dry density
ρ_{da}	density of dry air
ρ_l	density of liquid
ρ_v	density of vapour
ρ_w	density of water
σ	Boltzmann constant
σ_t	surface tension, Eq. (45)
χ_i	volume fraction of phase i
Φ	total potential of flow
Φ_L	phase lag, Eq. (31)
$\bar{\Phi}$	dimensionless coefficient accounting for porosity and extra path length around soil particles
Φ_o	osmotic potential
Φ_g	gravitational potential
ψ	capillary potential defined in equation
ψ_0	capillary potential at inflection point
ψ_{cB}	bubbling (or air entry) pressure
$\Delta\Psi$	edge factor
ω	annual frequency

1. Introduction

It is no surprise that energy conscious design and energy conservation have been the subject of international concern for many years. In Western Europe it is reported that 52% of energy delivered is consumed to maintain acceptable

environmental conditions within buildings [1]. Furthermore, the UK Department of Energy suggests that better design of new buildings could result in a 50% reduction in energy consumption and that appropriate design interventions could yield a reduction of 25% [2]. Opportunities for possible energy savings in the US also appear to be significant; one study has concluded that, if design and retrofits are carefully planned, energy efficiency of buildings could double by the year 2010, resulting in a saving of US$100 billion/year [3].

It is clear, therefore, that modern society demands energy efficient design of structures that also provide the practical requirements for adequate comfort levels. One part of the overall design processes requires an evaluation of likely heat losses to the ground.

The work presented in this report provides an overview of recent developments in the analysis and simulation of ground heat transfer from earth-contact structures. It is known that the thermal conductivity of the ground depends at least in part on its water content. Therefore, consideration is also given to the methods of analysis available to describe this aspect of the problem.

The main aims of the review are:

- to summarise the physical processes relevant to the analysis of ground heat transfer;
- to review methods of estimating soil thermal properties;
- to review methods of solving the heat transfer problem; including analytical, semi-analytical and numerical approaches;
- to provide a brief review of design guides used within the context of heat losses from slab-on-ground floors and basements;
- to consider the influence of ground moisture content changes on the ground heat transfer problem;
- to consider the determination of the relevant moisture transfer properties of soils;
- to briefly summarise the methods available for the analysis of coupled heat and moisture transfer problems;

2. Research background

The importance of energy conscious design of buildings has been recognised for many years [1–9]. However, notwithstanding the large amount of research that has been carried out to date, this is an area in which considerable research effort is currently being invested. Furthermore, it is evident from the technical literature that a diverse range of research activity has proved necessary to provide an adequate description of the varied and sometimes complex processes that occur within and adjacent to the building envelope. To date, the focus of attention has been naturally directed at the thermal behaviour of the superstructure of buildings from which it can be expected that significant heat losses may, if no insulation is

provided, take place. However, it is also recognised that significant heat losses may occur due to flow of heat from the inside of a building through the ground floor slab and into the foundation soils. New design guides are also being developed in this context [10] which complement existing guidelines [11].

The oil crisis in the early 1970s considerably increased energy bills and also had an influence on the perceived importance of heat transfer to the ground. Above-ground insulation of structures was improved and thus, thermal losses due to earth-contact became proportionally more important and could no longer be neglected. In a well documented survey carried out in the US, it was suggested that a waste of about \$5–\$15 billion a year could be attributed to heat transfer to the ground [12]. An indication of the relative heat losses through different parts of a structure has also been provided [13]. It was reported, for example, that in Ohio, US, an un-insulated basement accounted for 67% of the total envelope load when the above-ground part of the building was well insulated. Other studies claim that in cold climates the heat loss to the ground might be responsible for up to one third or even a half of total heat losses [14,15].

Other factors that also contribute to the growth in interest in ground heat transfer relate to novel construction, e.g. passive solar buildings and earth-sheltered buildings. Unconventional structures such as these are receiving progressively more attention. Advantage can be made of the high thermal mass of the ground for heat storage and/or for moderating internal climate variations. Several studies around the world have been undertaken in order to determine the benefits offered. For example, solar energy [16], air heat exchangers [17] and underground buildings [18–23] have all received recent attention.

It is clear from the above considerations that there is the need for adequate design and analysis of heat transfer to the ground. In some circumstances a relatively straightforward analytical approach may yield sufficient information for design purposes. However, in reality, many problems will involve complex geometry, time varying boundary data, thermal interaction of various adjacent materials (each with independent thermal characteristics) and other complexities. In these circumstances a more rigorous analysis may be required that will invariably necessitate the use of some form of approximation, numerical or otherwise. In this respect, numerous models have been developed for the above-grade part of buildings. However, until recently, heat loss to the ground had not been considered in an integrated manner. Progress is now being made; for example, a three-dimensional conductive ground heat flow module has been added to the computer program APACHE [24]. At the University of Athens, Greece, similar advances have been made within the environment of a computer program known as TRNSYS [25].

Historically, much of the work undertaken in this area is based on assumptions regarding the primary heat flow paths and mechanisms. For example, many analyses assume that the problem is either one- or two-dimensional. Such assumptions can be justifiably applied to a number of practical problems. However, in other cases, such as a detached domestic building, they may not be appropriate [26].

In recent work [27] the importance of multi-dimensional heat flow modelling has been revealed. Three simulation modes (one-, two- and three-dimensional) were used to predict the annual heating loads of an above-ground structure. A discrepancy of 22% was found between the two- and three-dimensional simulations and 41% between the one- and three-dimensional simulations. Others have also considered this aspect of the problem. The "*Danish Advanced Solar Low Energy Building*" programme revealed a discrepancy of over 50% between one- and two-dimensional heat load simulations [28]. Further studies can be found in the literature [29]. It appears, therefore, that geometrical simplification is not appropriate in a number of practical cases.

It is quite common for steady state heat transfer conditions to be the primary consideration in design. However, the large heat capacity of the ground delays the effect of any external temperature variations, resulting in a time lag effect (thermal inertia). In such cases, realistic representation of heat transfer variations will normally require some form of transient analysis to be performed. In this respect, numerical methods offer considerable flexibility. However, climatic boundary conditions need to be well defined for realistic modelling to be achieved.

Further complications arise in the analysis of ground heat transfer. In reality, the soil is often not homogeneous and thermophysical properties may therefore be spatially variable. In addition, it is known that the thermal properties of a soil may vary with temperature and soil moisture content. Thus, where significant variations in ground moisture content are anticipated, consideration of the effect on ground heat transfer may be necessary. It is also well established that in saturated soils where high flow rates occur beneath a structure, convective heat transfer may be significant. However, it appears from previous research that the influence of moisture content variations can be neglected in certain cases, e.g. soil of low permeability [16].

Heat flows around buildings clearly continues to be a subject of current interest [30–34]. Recent work has also included a full scale monitoring exercise carried out over a two year period [34]. In this work, a wide range of instrumentation was used to measure the thermal response of a modern commercial building — particular attention was given to heat and moisture migration beneath the building. It was concluded that the variation in moisture content was negligible in the 2 m of ground immediately under the centre of the floor slabs studied. However, near the edge of the building and outside the building, significant changes in ground moisture content were measured.

The demand for more accurate calculations has led to many studies in this field. To date, several methods have been developed to determine heat transfer to the ground. They can be grouped in various ways depending on their characteristics (e.g. the technique they use, time dependence, number of spatial dimensions, etc.). It is recognised that any attempt at categorising the wide range of approaches available is certain to have limitations. However, some attempts at categorisation have been made [35].

3. Mechanisms of ground heat transfer

The transport of heat in porous media may be induced by several mechanisms. The three most influential mechanisms are conduction, convection and the transfer of heat due to water phase change, also known as latent heat of vaporisation. Radiation is often assumed to be negligible and excluded from formulations.

Heat **conduction** is a process whereby heat is transferred from one region of the medium to another, without visible motion in the medium. The heat energy is passed from molecule to molecule. According to well established theory, the heat flux per unit area, q_{cond}, generated by conduction, may be written as:

$$q_{\mathrm{cond}} = -\lambda \nabla T \tag{1}$$

where λ is the thermal conductivity of the medium, T is the temperature and ∇ is the gradient operator.

Heat **convection** refers to the transport of heat in a fluid by means of circulation flows. Particle movement therefore exclusively induces convection effects. In soils, it is usually assumed that the soil structure (solid phase) is static and thus convection effects are only attributed to liquid and vapour transport.

The heat flux generated by liquid convection is then given as:

$$q_{\mathrm{lconv}} = c_{\mathrm{l}} \rho_{\mathrm{l}} \bar{v}_{\mathrm{l}} (T - T_{\mathrm{o}}) \tag{2}$$

where c_{l} is the specific heat capacity of soil water, ρ_{l} is the density of soil water, $\bar{v}_{\mathrm{l}}$ is the vector of water velocity and T_{o} is the reference temperature.

Similarly, the heat flux generated by vapour convection can be written as:

$$q_{\mathrm{vconv}} = c_{\mathrm{v}} \rho_{\mathrm{l}} \bar{v}_{\mathrm{v}} (T - T_{\mathrm{o}}) \tag{3}$$

where c_{v} is the specific heat capacity of soil vapour and $\bar{v}_{\mathrm{v}}$ is the vector of vapour velocity.

Latent heat of vaporisation is used when taking into account heat transfer caused by the transport of vapour in the medium and arises due to phase change. The magnitude of this contribution to the overall heat transfer will be dependent on the quantity of vapour transfer occurring and can be relatively significant when dry conditions prevail. The classical theory for heat transfer expresses the heat flux due to this contribution as:

$$q_{\mathrm{lat}} = L_0 \rho_{\mathrm{l}} \bar{v}_{\mathrm{v}} \tag{4}$$

where L_0 is the latent heat of vaporisation at T_{o}.

The total heat transfer, q_{h}, may thus be defined as:

$$q_{\mathrm{h}} = q_{\mathrm{cond}} + q_{\mathrm{lconv}} + q_{\mathrm{vconv}} + q_{\mathrm{lat}} \tag{5}$$

Radiation occurs across air spaces (or within a transparent medium) by heat energy propagated as electromagnetic waves. The temperature of the radiating body is the most important factor, the flow of heat being proportional to the

fourth power of the absolute temperature. In soils, radiation usually makes a negligible contribution to heat transfer. Its effect in sand is less than 1% of the overall heat transfer at normal atmospheric temperatures.

Radiation can play a significant part in heat transfer in dry, coarse, crushed-stone materials. For example, using a particle size of 20 mm gravel, it has been shown that the effect of radiation could amount to 10% of total heat transfer at normal temperatures [36]. It has also been reported that thermal conductivities of porous materials measured by a transient method can be higher than those obtained by a steady state method [37]. In this case, the difference was attributed to the contribution of radiation to the total heat transfer. The radiation contribution was later found to increase linearly with increasing thickness of the specimen used in the steady state method [38]. Measurements of the thermal conductivity of dry sands with the steady state guarded hot plate method also appear to point to possibly appreciable radiative heat transfer effects that decrease with decreasing temperature [39].

The properties and structure of soil water vary as the conditions and circumstances in soil change. In particular, changes may occur in the molecular configuration of the water depending on its degree of bonding (or adsorption) to the solid particles. Variations in molecular structure imply absorption or release of heat energy, which in turn contributes to the overall heat transfer behaviour of the material [40].

From consideration of conservation of heat energy in a representative control volume it is possible to derive the basic heat conduction equations. For example, the heat conduction equation can be posed in the following general form [41]:

$$\rho c \frac{\partial T}{\partial t} = \mathrm{div}(\lambda \ \mathrm{grad}\ T) + Q_{\mathrm{R}} \tag{6}$$

where ρ is the density of the material, c is the specific heat capacity, T is the temperature, t is the time, λ is the thermal conductivity and Q_{R} is the rate of heat generation within the medium. Eq. (6) can be recast according to the geometry and nature of the problem. For example, if the temperature of the material is not a function of time, the system is in steady state. If the material does not store or generate energy, the steady state form of the three-dimensional conduction equation in rectangular co-ordinates is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \nabla^2 T = 0 \tag{7}$$

Alternatively, a two-dimensional transient heat conduction problem with internal heat generation will require the solution of the following governing differential equation:

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + Q = \rho c \frac{\partial T}{\partial t} \tag{8}$$

The solution of Eq. (8) is clearly quite challenging, and implies material non-linearity. Further details on the derivation of these and other equations (and on the numerical solution of various forms of heat transfer equation) are provided elsewhere [41].

The ground heat transfer problem considered here generally requires the solution of a governing equation of a form similar to those above, depending on the nature of the problem in hand, the assumptions made and level of accuracy required. Many of the techniques considered in subsequent sections of the review are dedicated to the provision of either analytical solutions or numerical approximations to equations of this kind. In the first instance, the following section summarises techniques for estimating the primary thermal properties of soils.

4. Estimating thermal properties of soils

The **heat capacity** of a material is required when non-steady solutions are to be determined. In effect, the heat capacity defines the amount of energy stored in a material per unit mass per unit change in temperature (SI units J/kg K).

It is often satisfactory to calculate the heat capacity of soils by adding the heat capacities of the different constituents according to their volume fraction. For example, if χ_1, χ_2, χ_3 denote the volume fractions of three constituents of soil (air, water and solid), the heat capacity of the soil can be expressed as:

$$c = \chi_1 \rho_1 c_1 + \chi_2 \rho_2 c_2 + \chi_3 \rho_3 c_3 \tag{9}$$

where c_1, c_2 and c_3, are the specific heat capacities of the three soil constituents respectively. The heat capacity of a soil having more than three constituents can be calculated by simply adding more terms into Eq. (9). The specific heat capacities of some typical soil constituents are shown in Table 1 [42].

The volume fractions of a soil can be calculated from consideration of the soil porosity (volume of voids/total volume) and the degree of saturation (volume of water/volume of voids). Thus, the following relationships apply:

$$\chi_1 = 1 - \eta \quad \text{(solid fraction)} \tag{10}$$

$$\chi_2 = \eta S_l \quad \text{(water fraction)} \tag{11}$$

$$\chi_3 = \eta(1 - S_l) \quad \text{(air fraction)} \tag{12}$$

Tables 2 and 3 provide some further information which can be used to illustrate the application of this approach. For example, consider a sand comprising quartz ($c_1 = 2010$ J/kg K), water ($c_2 = 4186$ J/kg K) and air ($c_3 = 1.256$ J/kg K) and having a porosity of 0.5. Application of Eq. (9) for dry conditions (i.e. $S_l = 0$) yields a

volumetric heat capacity of 1005 J/kg K, whereas a saturated soil (i.e. $S_l = 1$) with the same porosity will have a volumetric heat capacity of 3098 J/kg K.

The basic process of heat conduction has been described previously. The constant of proportionality that relates the rate at which heat is transferred by conduction to the temperature gradient in a material is known as the **thermal conductivity** (SI units W/mK).

In the foregoing section it has been shown that the heat capacity of a soil can be expressed as a linear function of the volume ratios of the soil constituents. However, expressing the thermal conductivity as a function of the conductivities and volume ratios of the soil constituents is more complex and can only be achieved approximately.

Mathematically the problem is analogous to expressing the electrical conductivity or the dielectric constant of a granular material in terms of volume ratios and the electrical conductivities (or dielectric constants) of its constituents. Further information on the theoretical background to this problem has been provided in the literature [43].

Early attempts at solving the problem made use of the electric conductivity or dielectric constant of two-phase materials. If the soil constituents are assumed to have a distribution parallel to the direction of heat flow, the thermal conductivity of the soil can be expressed as:

$$\lambda = \chi_1 \lambda_1 + \chi_2 \lambda_2 \tag{13}$$

Table 1
Specific heat capacity and specific gravity of selected materials (after Clark [42])

Material	Specific heat capacity (J/kg K)	Density (kg/m^{-3})
Quartz	799	2650
Kaolin	937	2600
Calcium carbonate	870	2710
$CaSO_4$	816	2450
Fe_2O_3	690	5240
Al_2O_3	908	3700
$Fe(OH)_3$	946	3600
Orthoclase	812	2560
Oligaclase	858	2640
Potash mica	870	2900
Magnesia mica	862	2900
Hornblende	816	3200
Apatite	766	3200
Dolomite	929	2900
Talc	874	2700
Granite	803	2600
Syenite	833	2700
Diorite	812	2900
Andesite	833	2400
Basalt	891	3000

Table 2
Typical values of porosity (after Hough [45])

Soil type	Porosity range (%)
(1) Uniform materials	
(a) Equal spheres (theoretical values)	$26.0 < \eta < 47.6$
(b) Standard Ottawa sand	$33.0 < \eta < 44.0$
(c) Clean, uniform sand (fine or medium)	$29.0 < \eta < 50.0$
(d) Uniform, inorganic silt	$29.0 < \eta < 52.0$
(2) Well-graded materials	
(a) Silty sand	$23.0 < \eta < 47.0$
(b) Clean, fine to coarse sand	$17.0 < \eta < 49.0$
(c) Micaceous sand	$29.0 < \eta < 55.0$
(d) Silty sand and gravel	$12.0 < \eta < 46.0$
(3) Mixed soils	
(a) Sandy or silty clay	$20.0 < \eta < 64.0$
(b) Skip-graded silty clay with stones or rock fragments	$17.0 < \eta < 50.0$
(c) Well-graded gravel, sand, silt and clay mixture	$11.0 < \eta < 41.0$
(4) Clay soils	
(a) Clay (30–50% clay sizes)	$33.0 < \eta < 71.0$
(b) Colloidal clay (−0.002 mm ≥ 50%)	$37.0 < \eta < 92.0$
(5) Organic soils	
(a) Organic silt	$35.0 < \eta < 75.0$
(b) Organic clay (30–50% clay sizes)	$41.0 < \eta < 81.0$

where χ_1 and χ_2 are again volume fractions and λ_1 and λ_2 represent thermal conductivities of constituents, e.g. water and solid mineral. As shown below, the "**weighted arithmetic mean**" equation is known to over-estimate the thermal conductivity of soil [44].

An alternate approach is to assume that the soil constituents have a series

Table 3
Thermal conductivity and heat capacity of some soil materials (after De Vries [43])[a]

Substance	Thermal conductivity (W/mK)	Specific heat capacity (J/kg K)	Density (Kg/m^3)
Quartz	8.79	2010	2660
Clay minerals	2.93	2010	2650
Organic matter	0.25	2512	1300
Water	0.57	4186	1000
Ice	2.18	1884	920
Air	0.025	1.256	1.25

[a] These values have been converted to SI units from the original reference.

distribution that is perpendicular to the direction of heat flow, the thermal conductivity of the soil may be expressed as:

$$\lambda = \frac{\lambda_1 \lambda_2}{\chi_1 \lambda_2 + \chi_2 \lambda_1} \tag{14}$$

This is the so-called "**weighted harmonic mean**" equation, which is known to under-estimate the thermal conductivity of the soil [44].

Also a "**weighted geometric mean**" equation was used by Woodside and Messmer [44] to represent the thermal conductivity, in the form:

$$\lambda = \lambda_1^{\chi_1} \lambda_2^{\chi_2} \tag{15}$$

This approach was found to give an intermediate value between the arithmetic mean and the harmonic mean equation.

For the purpose of illustration, Fig. 1 provides a comparison of thermal conductivity values calculated from the arithmetic mean, harmonic mean and geometric mean equations. The results are plotted against porosity (volume of voids divided by the total volume of soil). Since the porosity indicates the maximum water content a soil can achieve, it is clearly a parameter of importance. Table 2 provides a summary of porosity values that may be expected for a variety of different soil types (after Hough [45]).

The above three equations can be easily extended for a soil containing more than two constituents. For parallel distribution:

$$\lambda = \chi_1 \lambda_1 + \chi_2 \lambda_2 + \chi_3 \lambda_3 \tag{16}$$

and for series distribution:

$$\lambda = \frac{\lambda_1 \lambda_2 \lambda_3}{\chi_1 \lambda_2 \lambda_3 + \chi_2 \lambda_3 \lambda_1 + \chi_3 \lambda_1 \lambda_2} \tag{17}$$

The geometric mean is then given as:

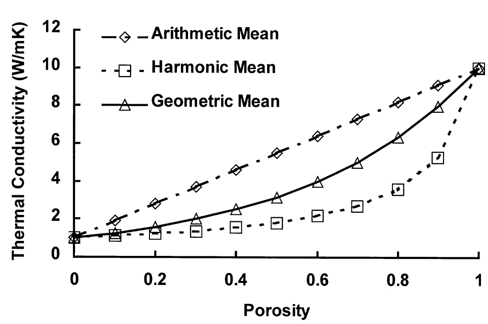

Fig. 1. The relationship between thermal conductivity and porosity.

$$\lambda = \prod_{i=1}^{n} \lambda_i^{\chi_i} \tag{18}$$

where n is the number of constituents and Π is used in the traditional sense to imply product terms. De Vries [46] proposed an alternative expression for the calculation of thermal conductivity of the following form:

$$\lambda = \frac{\sum_{i=0}^{n} k_i \chi_i \lambda_i}{\sum_{i=0}^{n} k_i \chi_i} \tag{19}$$

where k_i is the ratio of the average temperature gradient in the solid granules. The initial value, k_0, is taken as equal to unity. The calculation of k_i is difficult; an exact mathematical expression for k_i was provided for the following restricting conditions: (a) the granules are of ellipsoidal shape; and (b) the granules are so far apart that they do not influence each other. In this case, for a two constituent soil, k_i can be found from the equation:

$$k_i = \frac{1}{3} \sum_{a,\ b,\ c} \left[1 + \left(\frac{\lambda_1}{\lambda_0} - 1 \right) g_\mathrm{a} \right]^{-1} \tag{20}$$

g_a is calculated from the equation:

$$g_\mathrm{a} = \frac{1}{2} abc \int_0^\infty \frac{\mathrm{d}u}{(a^2+u)^{3/2}(b^2+u)^{1/2}(c^2+u)^{1/2}} \tag{21}$$

where a, b and c are the axes of the ellipsoidal granules.

Van Rooyen and Winterkorn [47] presented the following equation, based on the original work of Nusselt [48], for the thermal conductivity of a fissured body, taking into account the effect of radiation:

$$\lambda = \frac{L_\mathrm{s} + L_\mathrm{a}}{\dfrac{L_\mathrm{s}}{\lambda_\mathrm{g}} + \dfrac{1}{\dfrac{\lambda_\mathrm{a}}{L_\mathrm{a}} + 4\sigma T^3}} \tag{22}$$

where λ_a and λ_g are the thermal conductivities of the air and solids respectively, T is the absolute temperature and σ is the Boltzmann constant.

The fissured body was considered to consist of parallel solid plates of thickness L_s, separated by air layers of thickness L_a with heat flowing across them. This equation was applied by Van Rooyen and Winterkorn [47] to calculate the thermal conductivity of dry soils; however, values so obtained were about one-fifth of the measured values. This was primarily due to the fact that soil particle arrangements in practice are unlikely to be ordered in parallel configuration.

In addition to the theoretical methods outlined above, the thermal conductivity of soil has frequently been expressed in terms of empirical equations. These tend to be suitable only for the particular soils tested under designated conditions, and therefore lack generality.

For example, an empirical expression for thermal conductivity was presented by Makowski and Mochlinski [49]. This expression can be written in SI units as:

$$\lambda = (a \log_{10} m + b)10^{z} \tag{23}$$

where

$$a = 0.1424 - 0.000465p \quad b = 0.0419 - 0.000313p$$

and

$$z = 6.24\rho_{\mathrm{d}} \times 10^{-4}$$

In the above, m is the moisture content of the soil as a percentage of dry soil weight, ρ_{d} is the dry density and p is the percentage of clay in the soil.

Thomas et al. [50] provided the following relationship between thermal conductivity and the degree of saturation:

$$\lambda = 0.62 + 3.976S_{\mathrm{l}} + 2.687S_{\mathrm{l}} \log(S_{\mathrm{l}}) - 3.313S_{\mathrm{l}}^{2} \tag{24}$$

where S_{l} is the degree of saturation of water. This equation was employed in the analysis of coupled heat and moisture transfer within an unsaturated clay.

Although Eq. (19), suggested by De Vries [46], appears difficult to use, the author clearly demonstrated the calculation procedure for three soil types: sand, clay and a fibrous brown peat. Since this method offers considerable flexibility over some of the other methods described above, a brief description of the main observations that De Vries reported on the application of the method is provided below.

For a soil referred to as "Fairbanks" sand, the calculated thermal conductivities were found to be in excellent agreement with the experimental values (see Table 4). The difference between the calculated and measured thermal conductivities was found to be normally less than 10%. The sand consisted of 59.4% (by weight) quartz, 40.6% feldspar and nominal amounts of other minerals. The specific mass of the dry materials was 2.72 g/cm^3. The specific mass of the quartz was 2.66 g/cm^3 and the average specific mass of the other soil minerals was 2.80 g/cm^3. The volume percentages of quartz and other minerals were 60.6 and 39.4%, respectively. In the calculation the following values were employed: $\lambda_1 = 8.7864$ W/mK for quartz, $\lambda_2 = 2.9288$ W/mK for other minerals, $\lambda_{\mathrm{w}} = 0.56$ W/mK for water and $\lambda_{\mathrm{a}} = 0.02468$ W/mK for air.

In contrast, for the "Healy" clay, the difference between calculated and measured thermal conductivities reached as much as 40%, as shown in Table 5. The soil consisted mainly of clay (55%), with additions of quartz (22.5%), coal (22%) and some other minerals (0.5%). The specific mass of the dry material was

Table 4
Calculated and measured thermal conductivity for Fairbanks sand (De Vries [43])

χ_w	χ_s	χ_a	λ_e (measured) (W/m K)	λ_c (calculated) (W/m K)
0.212	0.66	0.128	2.297	2.268
0.203	0.71	0.087	2.540	2.636
0.184	0.632	0.184	2.079	1.971
0.117	0.705	0.178	2.192	2.238
0.112	0.665	0.223	2.029	1.908
0.102	0.691	0.207	2.222	2.063
0.101	0.631	0.268	1.569	1.632
0.05	0.71	0.24	1.791	1.807
0.047	0.665	0.288	1.443	1.494
0.043	0.631	0.326	1.222	1.272
0.026	0.727	0.247	1.201	1.172
0.025	0.705	0.27	0.920	1.046
0.024	0.665	0.311	0.808	0.837
0.021	0.631	0.348	0.577	0.711
0.004	0.71	0.286	0.052	0.050
0.004	0.665	0.331	0.377	0.397
0.003	0.629	0.368	0.331	0.335

2.59 g/cm^3 and the thermal conductivity λ_s was 2.51 W/mK. It was concluded that the theoretical procedure tends to overestimate the value of the thermal conductivity for the Healy clay with low moisture content. It was also thought that the measured thermal conductivities were smaller than expected at low moisture content.

Table 5
Calculated and measured λ for Healy clay (De Vries [43])

χ_w	χ_s	χ_a	λ_e (measured) (W/m K)	λ_c (calculated) (W/m K)
0.359	0.641	0	1.540	1.531
0.45	0.499	0.051	1.226	1.192
0.402	0.444	0.154	0.824	0.979
0.334	0.579	0.087	1.347	1.284
0.304	0.517	0.179	0.912	1.050
0.27	0.671	0.059	1.628	1.502
0.256	0.581	0.163	1.188	1.180
0.231	0.519	0.25	0.950	0.954
0.163	0.581	0.256	0.883	0.971
0.144	0.519	0.337	0.640	0.820
0.095	0.575	0.33	0.594	0.766
0.091	0.525	0.384	0.418	0.695
0.041	0.521	0.438	0.297	0.356
0.038	0.457	0.505	0.205	0.272
0.033	0.396	0.571	0.159	0.201

For the highly organic "Fairbanks" peat, the calculated and measured thermal conductivities presented in Table 6 show a good agreement. The largest difference between measured and calculated results is only 20% among 12 samples. De Vries assumed $\lambda_s = 0.251$ W/mK in the calculation.

Overall, the accuracy of theoretical estimation of the thermal conductivity is better than 10% in most cases. This degree of accuracy, according to De Vries, will be sufficient for many applications.

Woodside and Messmer [44] carried out experiments measuring the thermal conductivity of an unconsolidated saturated sand. Measured values were compared with calculated results using a number of different methods, some of which are described above. They found that the weighted arithmetic mean approach gave a much greater value than that measured and the weighted harmonic mean gave a much smaller value than the measured result. De Vries' method generally agreed fairly well with the experimental data. However, this equation under-estimated overall soil thermal conductivity when the fluid phase had a particularly small thermal conductivity. Subsequently, experiments were carried out on consolidated rocks. On this occasion, the weighted geometric mean approach was found to best fit the data in comparison to five other methods.

There are other useful methods of calculating thermal conductivity of soils such as Johansen's method [51]. A valuable critique of this and other methods was provided by Farouki [52].

Turning attention to some of the building materials used in developing countries, a number of studies have reported on thermal properties of soil-based building materials. Within this area, it has been noted that few scientific studies on thermal properties have been carried out [53]. The available data should therefore be treated with caution since they often do not cover parameters such as density, moisture content, soil type, etc. Table 7 summarises some of the information available for stabilised soil based blocks [54–56].

Table 6
Calculated and measured λ for Fairbanks peat (De Vries [43])

χ_w	χ_s	χ_a	λ_e (measured) (W/m K)	λ_c (calculated) (W/m K)
0.79	0.21	0	0.448	0.481
0.676	0.292	0.032	0.448	0.435
0.66	0.171	0.169	0.402	0.385
0.614	0.244	0.142	0.372	0.381
0.399	0.169	0.432	0.247	0.243
0.38	0.248	0.372	0.251	0.251
0.322	0.087	0.591	0.134	0.155
0.25	0.169	0.581	0.138	0.146
0.229	0.095	0.676	0.100	0.126
0.135	0.088	0.777	0.092	0.096
0.032	0.256	0.712	0.063	0.067
0.023	0.164	0.813	0.050	0.050

The Chartered Institution of Building Services Engineers provides thermal properties for sand, silt, gravel and clay, etc. under given conditions [11]. A moisture correction factor table has also been provided elsewhere [57].

5. Solving the ground heat transfer equations

5.1. Analytical and semi-analytical solutions

Analytical solutions of heat transfer equations were the first available and generally assume some simplification of the problem. However, in certain cases (simple configurations) these methods can be very powerful since they provide fast exact solutions. Semi-analytical methods are similar in the mathematical approach they use, but generally require a computer-based solution to be developed (e.g. to efficiently perform numerical integration).

A number of solutions to the steady-state heat conduction equation can be found in the literature. For example, Latta and Boileau [58] analysed a measured temperature profile in the ground surrounding a basement. During a winter period, it was observed that the flow of heat to the Earth's surface followed circular paths (see Fig. 2). Knowing the thermal conductivity of the soil λ (W/m °C) and calculating the length of these paths (arcs) from a point in the below-grade wall, the heat loss Q_z (W/m^2) at depth z (m) was given by:

$$Q_z = \frac{T_i - T_s}{R_w + R_{ins} + (\pi z/2\lambda)} \tag{25}$$

where $T_i - T_s$ is the temperature difference between the inside and the ground surface, R_w is the thermal resistance of the wall and R_{ins} is the thermal resistance of the insulation.

In this method, the subgrade wall is divided into 0.3 m length segments and Eq. (25) is used as many times as the entire wall length requires. The basement floor is treated in a similar manner. Tabulated U-values for 0.3 m strips of wall are given for various depths, path lengths and insulation levels. The ASHRAE guide [59] adopted this method and some modifications were included in 1985. However, some criticisms of the method have arisen: (i) the method ignores heat loss to the ground at depth, which is a limitation for summer period calculations; and (ii)

Table 7
Thermal conductivity of stabilised soil blocks

Thermal conductivity (W/m K)	Density (kg/m^3)	Source
0.46–0.81	1200–1700	United Nations Centre for Human Settlements [54]
0.50–0.70	1500–1900	The International Labour Office, Geneva [55]
0.58–0.65	1750–2000	University of Nairobi [56]

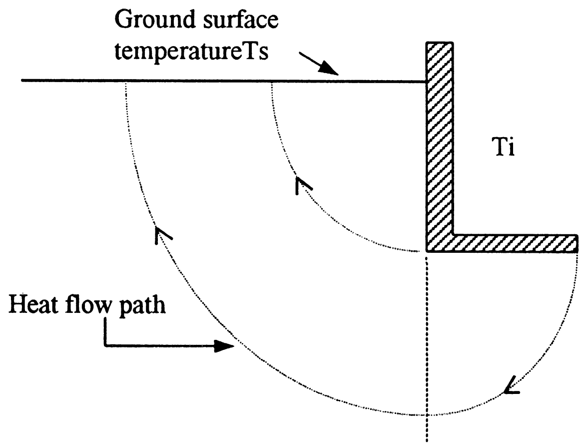

Fig. 2. Assumed heat flow paths (Latta and Boileau [58]).

when the walls are partially insulated, the heat flow paths are no longer concentric as described, but have a shape somewhere between circular and vertical lines.

Further developments have been made where a solution for an uninsulated semi-infinite slab-on-grade has been presented [60,61]. The work may be viewed as a continuation of Muncey's Fourier analysis [26], which involved dividing the floor surface into equally spaced identical rectangular slabs. In 1983, Delsante [60] considered the floor as a unique entity and used Fourier transforms to obtain explicit expressions for: (i) two-dimensional heat flow under periodic variations of boundary conditions; and (ii) three-dimensional steady-state heat flow for a rectangular floor (Fig. 3). An approximate solution was then derived for the periodic three-dimensional case. The temperature under the wall at the ground level was assumed to change linearly. In further work [61], the surface film resistance was included and an analytical expression for two-dimensional steady-state heat flow was proposed. The theory was also based on Fourier transformation and assumed the same thermal resistance for the soil and the floor, which was thus treated as a uniform semi-infinite solid.

A semi-analytical method using Green's functions to solve a three-dimensional dynamic heat flow equation was presented by Kusuda and Bean [62]. The solution was provided in the following form for an insulated slab-on-grade floor:

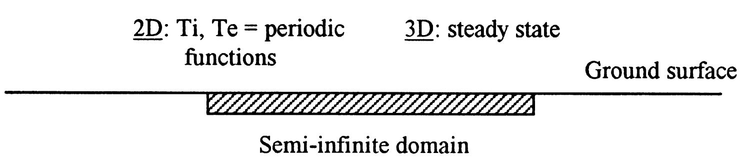

Fig. 3. Diagrammatic representation of Delsante's approach [60].

$$Q = \frac{\lambda}{L}(T_{\rm R} - T_z) \tag{26}$$

where Q is the floor heat flux (W/m^2), λ the soil thermal conductivity (W/m °C), L the thickness of earth (m) and $T_{\rm R}$ is the mean temperature of the slab (°C). T_z is calculated by Green's technique and is the monthly average subfloor temperature at a given depth z. An approximation was also included to take into account the effect of floor insulation.

Work can also be found in the literature on an analytical solution of dynamic three-dimensional heat flow to the ground from a building [14]. This approach was divided into three components: (i) a steady-state heat transfer; (ii) a periodic variation of the outdoor temperature; and (iii) a step variation of the outdoor temperature. The superposition of these different components of the solution yields an expression for heat loss (Fig. 4). The method assumes a constant indoor temperature and a homogeneous semi-infinite ground with a fixed temperature value at depth.

Further extensions of the above work have also been made. For example, the inclusion of an even thermal insulation layer has been addressed for a rectangular slab-on-grade [63]. A solution taking into account the effect of ground water flow, at either a finite or an infinite rate, can be found in more recent references [64,65].

Separately, a semi-analytic calculation method has been suggested for the determination of two-dimensional temperature profiles and heat flow under a house under steady-state conditions [66]. The method, which assumes a semi-infinite slab, can accommodate a variable thickness of floor insulation. The temperature is expressed in the form of a Fourier series and an iterative numerical calculation is used to compute Fourier coefficients.

Krarti's semi-analytical method is applicable to both slab-on-grade and basement configurations [67–69]. The work is based on the *Interzone Temperature Profile Estimation technique* (ITPE) in which the ground, slab or basement is divided into several zones of rectangular shape. The temperature boundary conditions between the different zones are arbitrarily fixed profiles (based on physical considerations). The solution in each zone is then found according to selected interzonal functions. Solutions are provided for steady-state and periodic conditions in two- and three-dimensional configurations, while transient solutions

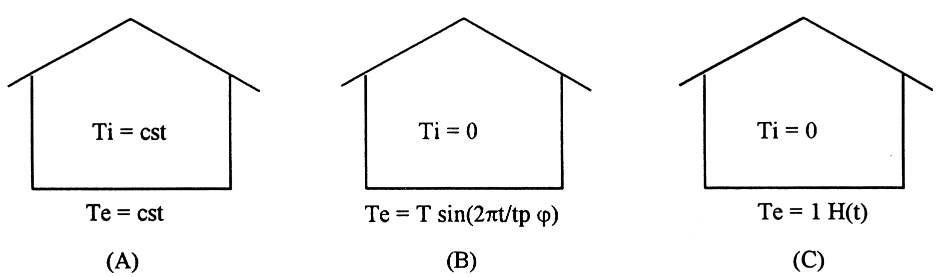

Fig. 4. Superposition adopted by Claesson and Hagentoft [14].

are presented only for two-dimensional heat flow. This method allows the addition of insulation and can be applied to various geometry.

Other work employing Fourier-series boundary technique has been published in response to the perceived shortfalls of computer-based solutions. Semi-analytic solutions for two-dimensional periodic steady-state conditions were developed [70,71].

Transient heat losses from walls in contact with the ground have also been determined by the use of "response factors" [72]. This work focuses on determination of response factors for elements of the structure (walls) which are in contact with the ground where thermal transfers can no longer be considered as unidirectional (thermal bridging). The response factor is a pulsed series thermal response to a unitary elementary input (thermal flow or temperature) as shown in Fig. 5. The work describes the integration of response factors determined for walls in contact with the ground in pulsed-type calculations of thermal loads.

More recently, an analytical model to predict ground temperature variations through a number of seasons was presented [73]. In order to aid the design process, when experimental measurements are not available, an analytical procedure was presented that included several parameters related to the season, weather, thermal properties of the soil, surface-air convection, humidity, geographic situation and site orientation.

Other work has focused on the determination of solid floor U-values. In general, this type of research utilises and develops work originally proposed by Macey [74]. For example, methods for the addition of internal or external insulation to the basic framework and extension to various shapes and more realistic conditions have been proposed [75,76]. Reconsideration of the correction applied to Macey's formula to take into account finite floor dimensions has also been the focus of some attention elsewhere [77,78].

Table 8 provides a summary of some of the above methods along with some comments regarding their scope and limitations.

5.2. Numerical methods

As discussed before, when a problem can be justifiably simplified, analytical methods can be extremely useful. However, for more complex problems numerical methods offer a more flexible approach. In particular, multi-dimensionality,

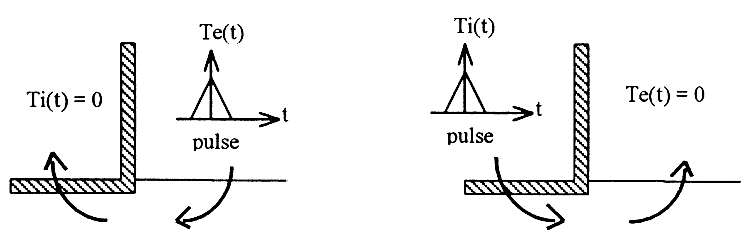

Fig. 5. Generation of response factors (Achard et al. [72]).

Table 8
Summary of some analytical and semi-analytical techniques

Method	Scope	Limitations	Source
Analytical, steady-state	Heat loss from slabs-on-ground and basements	Ignores heat losses to the deep ground: not valid for summer calculations	Latta and Boileau [58]
Analytical, Fourier analysis: periodic: 2-D explicit, 3-D approximation; steady-state: 3-D	Heat loss from slabs-on-ground	Semi-infinite solid, rectangular shape of slab, not valid for basements	Delsante et al. [60]
Semi-analytical, Green's functions: dynamic	Heat loss from slabs-on-ground	Approximate solution if insulation added, not valid for basements	Kusuda and Bean [62]
Analytical, superposition of steady-state, periodic and unit-step solutions	Heat loss from slabs-on-ground and basements	Difference complications of the process cannot be handled at the same time (i.e. in one solution), e.g. water table, uneven insulation	Claesson and Hagentoft [14], Hagentoft and Claesson [63] and Hagentoft [64–66]
Semi-analytical: steady-state, periodic: 2- and 3-D; transient: 2-D	Heat loss from slabs-on-ground and basements	Predefined temperature boundary conditions arbitrarily fixed between different zones of the domain	Krarti [67,69]
Semi-analytical, Fourier analysis: period 2-D	Heat loss from slabs-on-ground and basements	Semi-infinite solid for transient calculations, no insulation	Shen and Ramsey [70,71]

complex geometry and dynamic boundary conditions can be readily included. Many numerical solutions usually rely on the use of either finite difference or finite element techniques (or some combination thereof).

One of the first numerical earth-contact simulations was reported in 1963 [79]. The approach adopted was based on an explicit finite difference algorithm. A three-dimensional model was used to calculate temperature, humidity and heat transfer in experimental underground shelters. Simultaneous heat and vapour transport was considered and the program took into account solar radiation and convective heat transfer at the Earth's surface.

Coupling of ground heat transfer to more general building simulation codes appeared by 1979 [18]. Here a two-dimensional finite difference model was used to predict transient heat transfer from earth-covered buildings. The discretised region (structure and ground) was in the form of an axisymmetric cylinder. The outdoor and indoor temperature variations were prescribed functions of time and the program could handle random external and internal temperature profiles.

Wang [80] continued the work of Latta and Boileau [58] and showed that the heat flow from a partially insulated basement does not follow circular paths but something between circular and vertical lines. A two-dimensional finite element program was developed and used to analyse various configurations of slabs and basements. This study formed the basis of the "F_2" factor determination, which is suggested in the current version of the *ASHRAE Fundamentals* guide.

For some problems a multi-dimensional approach appears necessary. For example, extensions of a two-dimensional finite difference model to accommodate three-dimensional solutions can be found in the literature [81]. In order to integrate this solution into existing models (many of which were one-dimensional), the procedure was transformed to an equivalent one-dimensional solution.

Szydlowski and Kuehn [82] employed an implicit finite difference technique to determine the thermal impact of different insulation configurations (internal, external, level and location) on various structures (basements, earth-beamed walls and earth-covered shelters). It was also found that if the soil properties were periodically varied, the annual cycle could be modelled more rapidly and with insignificant loss of accuracy. Further application of the finite difference methods can be found in a two-dimensional model developed to study heat losses from the foundations of five Danish test houses [83].

The general finite element thermal analysis program ADINAT has been used to determine two-dimensional heat transfer between an earth-sheltered building and the ground [84]. Effects of phase change of water in the soil were included in the model. A parametric study showed that the thermal conductivity of the soil (which is function of the soil moisture content) significantly influences the simulation results and must be carefully determined.

Three-dimensional heat loss from rectangular basements and slabs to the ground has been estimated via an extended two-dimensional framework by Walton [29]. The technique used the "R-C electric analogy" which leads to equivalent finite difference equations. Table 9 details the analogy for a simplified one-dimensional model. All different parts of the equivalent electrical circuits in

the whole domain are connected together to build the discretised equations. Ambrose [81] presented an approach which is similar in the sense that a two-dimensional finite difference model was used to estimate three-dimensional heat losses from rectangular slabs.

Roux et al. [85] used modal analysis to determine the thermal transfer between a building and the surrounding ground. In this technique, the problem was divided into a number of sub-systems (one-dimensional for walls and two-dimensional for the floor). The finite difference technique was then used to obtain the discretised equations in each sub-system and the resulting general matrix formulation solved by modal analysis (reduction of the system by choosing an appropriate time constant according to the eigenvalues). The technique was described by the authors to be computationally efficient (although no specific details were provided).

Within the context of the *Japanese Optimum Use of Solar Energy Programme*, measurements were recorded over a five year period in a semi-underground house [86,23]. The measured data was compared to a two-dimensional finite element simulation for various configurations: with and without solar gain, periodic heating, etc. The numerical program developed was used specifically to explore the effect of varying the location of insulation.

Finding that there was a lack of multi-dimensional simulation work, some researchers [15,87] developed a computer program to obtain the three-dimensional solution of the diffusion equation. An implicit finite difference technique was used to determine heat transfer from slab-on grade floors. The code took into account solar and long wave radiation, and convection and evaporation at the Earth surface. A sensitivity study showed that the thermal conductivity of the soil is important. For example, the annual mean heat loss from an uninsulated square shaped slab (45×45 m) was analysed. It was found that a change from 0.5 to 2.0 W/m K in the soil conductivity resulted in an increase of the heat loss from approximately 2500 to 7000 W.

A two-dimensional finite difference program to model heat exchanges between a slab-on-grade and the ground in hot climates has also been reported [88]. This study was undertaken to investigate the effect of floor insulation in climates where both heating and cooling performance must be considered. It was found that the insulation level has to be determined in such a way that it minimises the cooling load in summer (by transferring a part of the internal heat to the ground through

Table 9
Electrical analogy in thermal systems

Electrical variables	Thermal variables
Potential	Temperature
Intensity	Heat flux
Resistance	Resistance
Capacity	Capacity

the slab) and the heating load in winter (by being efficient enough to reduce heat loss to the ground).

In response to a perception that design tools were often not very easy to use and were unnecessarily complex, Richards and Matthews [89] integrated a generally applicable numerical program into an existing simplified ground-contact model. The analytical formulation proposed by Anderson [75] was used in this work.

Recently the results of a research programme that involved direct measurement of the thermal response of a full-scale modern commercial building have been published [30–34]. Data was collected over a two-year period and results included transient variations of heat flux through the floor slab, air temperature, ground temperature and ground moisture content. Some preliminary numerical analysis of the data via the use of a general purpose finite element heat transfer programme has been performed.

Other recent developments include the addition of three-dimensional ground heat transfer modules within general purpose building energy codes [24,25,27]. These methods employ the finite volume technique following Patankar [90].

5.3. Simplified methods

For the purposes of this review, these methods are considered to be simplified algorithms that can be used with the aid of a hand calculator. From this point of view, design guides could be classified in this group. However, given the practical importance of design guides, they are considered separately in the following section.

Simplified methods are generally derived from analytical, numerical or experimental calculations. As discussed previously, earth-contact heat transfer may be influenced by a number of factors (e.g. climatic data, thermophysical properties, geometric configuration, insulation, etc.). Therefore, methods which have necessary simplifications of the physical problem have limited applicability. However, within the context of their stated aims, e.g. to yield accurate calculations with a minimum of parameters, these methods have been found to provide useful information about the thermal performance of structures. Some of these methods are reviewed below.

One method, based on observed basement heat losses from a building in Canada, was presented by Swinton and Platts [91]. The method was successfully applied for three locations, but could not be generalised to other circumstances.

Within the context of a comprehensive study of large earth-sheltered buildings at the University of Minnesota, a two-dimensional implicit finite difference model to simulate heat transfer to the ground was developed [92]. The model was used to calculate annual heating season and cooling season heat flows, Q, for various cases (insulation, slab-on-grade, basement, crawl-space configuration, etc.). The results obtained were simplified to the following regression equations [13]:

$$Q = B_0 + \frac{B_1}{R} + B_2(HDD/100) + B_3(CDD/100) + B_4\frac{(HDD/100)}{R} + B_5\frac{(CDD/100)}{R} + B_6(HDD/100)(CDD/100) + B_7R(CDD/100) \tag{27}$$

where B_0–B_7 are tabulated coefficients for various configurations, R is the thermal resistance of the structure, HDD are heating degree-days and CDD are cooling degree-days. The coefficients B_0–B_7 alter if a different base temperature for degree-day calculation is used. A limitation of this method comes from the single set of soil thermal properties and the fixed indoor temperature used to develop the correlation. Further work on this approach has also been carried out [93,94], where the temperature setting assumptions have been removed to allow a more general application of the technique.

A further method known as the *Decremented Average Ground Temperature* method (DAGT) is also available [95]. This approach takes into account the change of ground temperature due to the heat loss from the building. A finite difference programme was used to compute the heat flow to the ground and the results obtained were used to determine the following expression:

$$Q = F_d UA(T_R - T_S) \tag{28}$$

where U is the U-value of the wall (W/m^2 °C), A the wall area (m^2) and $T_R - T_S$ is the temperature difference between the room and the soil (°C). The coefficients F_d are tabulated "decrement factor" values and are given as functions of soil thermal conductivity and wall thermal resistance. This method applies only for entirely underground walls and is not applicable to floors.

In 1983, Mitalas presented a detailed method for predicting the heat loss from basements and slab-on-grade floors [96,97]. It was one of the first methods to allow the determination of heat transfer to the ground at any time of the year. Underground walls and floors were divided into five segments and the total heat flow was estimated by summing the losses of the different zones Q_n (n = 1–5) using "linking" factors. Q_n was expressed as follows:

$$Q_{n,\,t} = Q_{m,\,n} + Q_{A,\,n,\,t}\ \sin\frac{2\pi t}{12} \tag{29}$$

where Q_m is the annual heat loss (W/m^2), Q_A is the annual amplitude of the heat loss (W/m^2) and t is the time. Two- and three-dimensional finite element models were used to compile tables of heat loss factors for a variety of configurations (insulation, foundation type). Experimental data were used to validate the approach.

Yard et al. [98] presented a two-dimensional finite element analysis applied to simulate heat losses from a basement. Expressions were developed in terms of non-dimensional parameters. As with Mitalas's theory, the ground temperature was assumed to be a sinusoidal function of time and heat loss from the basement can be determined at any time of the year. The total heat flow to the ground was

calculated from the sum of the floor (f) and the wall (w) components:

$$Q = U_f A_f (T_b - T_{g,\ f}\ ) + U_w A_w (T_b - T_{g,\ w}) \tag{30}$$

where A is the floor area (m^2), T_b is the basement indoor temperature (°C) and T_g is the time-dependent effective ground temperature (°C). Relations were given for the calculation of U-values U_f and U_w (W/m^2 °C). These were expressed as functions of the soil conductivity, insulation configuration and basement depth.

Using the ITPE technique discussed previously, a simplified method for heat loss calculations from both slab-on-grade and basements has been presented quite recently [69]. Non-linear regression was used to develop an expression for heat loss from the foundation to the ground where Q (W/m^2) varies sinusoidally with time and is written as:

$$Q = Q_m + Q_a \ \cos(\omega_t - \Phi_L) \tag{31}$$

Q_m is the mean annual heat loss (W/m^2), Q_a is the annual amplitude (W/m^2), ω is the annual frequency and Φ_L is the phase lag between heat loss and soil surface temperature. These three coefficients are taken as functions of soil properties, foundation dimensions, insulation U-values and configuration, indoor air temperature and ground surface temperature. They were determined using 2000 different slab-on-grade and basement configurations (this is the first work which included such a large number of configurations; in comparison, others [96,97] used 100 configurations).

6. Design guides for earth contact structural components

This section of the review provides a brief insight into the various guidance documents that are available to assist with the thermal design of earth-contact structures. Such *design guides* are generally based on research undertaken with specific end-users in mind. They are typically co-ordinated by organisations representing practitioners; for example, the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), or in the UK, the Chartered Institution of Building Services Engineers (CIBSE).

The method presented in the *ASHRAE Handbook* [59] is probably one of the most widely used and is based on the previously cited work of Boileau, Latta and Wang. For basements, tables provide heat loss values for one type of soil conductivity (1.38 W/m °C) according to various depths, path lengths and insulation. For slab-on-grade floors, the heat flow to the ground is given as:

$$Q = F_2 P (T_i - T_o) \tag{32}$$

where P is the perimeter of the exposed edge of floor (m), T_i and T_o are, respectively, indoor and outdoor temperatures and F_2 are tabulated heat loss

coefficients; they are provided for different insulation/wall configurations (W/m °C).

In the UK, the *CIBSE Guide* [11] is one of the primary guidance documents. It is essentially based on Macey's steady-state formula [74]. It is only valid for uninsulated rectangular slab-on-grade floors. The following expression gives the floor U-values (W/m^2 °C):

$$U = \frac{2\lambda_e}{1/2b\pi}\arctan h\left(\frac{1/2b}{1/2b + 1/2w}\right)\exp\left(\frac{1/2b}{l_f}\right) \tag{33}$$

where λ_e (W/m °C) is the "Earth" thermal conductivity, b and l_f are, respectively, the breadth and the length of floor (m) and w is the thickness of wall (m). The CIBSE guide describes modification of the equation to include insulation.

The French guide, published by the "*Association des Ingénieurs de Climatisation et de Ventilation de France*" (*AICVF*), gives expressions for the calculation of heat losses from floors and walls in contact with the ground. In all cases the heat flow Q (W) is written as:

$$Q = K_s L(T_i - T_o) \tag{34}$$

where L is the length of the exposed edge, T_i is the indoor temperature and T_o is the outdoor temperature. K_s (W/m °C) is a coupling coefficient which depends on the configuration (floor or wall), the depth, the thickness, soil and basement thermal conductivities and convective coefficients. For each case an expression is given for calculating K_s values.

The European Standard [10] is the most detailed of those dealt with in this section and accommodates a large number of configurations. The general formulation for the calculation of U-values (W/m^2 °C) is as follows:

$$U = U_0 + 2\Delta\Psi/B' \tag{35}$$

where U_o is the basic thermal transmittance of slab-on-grade floor (W/m^2 °C), $\Delta\Psi$ is an edge factor (W/m °C) and B' is the characteristic dimension of floor (m). The procedure requires calculation of the U_0, ignoring edge insulation but including any overall insulation. Then the edge factor, $\Delta\Psi$, is calculated for either horizontal or vertical edge insulation. $\Delta\Psi$ is described in the code as a correction factor related to the detail of the floor edge. The procedure for its determination is fully described in the standard.

U-value calculations are detailed in the French guide for various configurations: slab-on-grade, suspended floor, basement, etc. Monthly, seasonal and annual heat transfer rates are also provided and the different coefficients used in the calculations are given in accordance with each configuration case.

Additional guidance can be found in the Building Research Establishment (UK) digest on "Heat losses through ground for slabs" [99]. The basis for calculating standard U-values is presented. Design of solid ground floors and suspended ground floors is also briefly considered.

7. The influence of ground water content changes on heat transfer

There is an abundance of literature available on the analysis of heat and mass (moisture) transfer in other research disciplines. However, to date relatively little attention has been given directly to the influence of ground moisture content variations on the thermal properties of foundation soils and the concomitant implications on heat losses from buildings.

As stated above, the thermal properties of soils are fundamentally linked to the properties and proportions of individual constituents (water/air/solid). From these considerations it is clear that the moisture content of a soil is an important factor contributing to the average thermal properties of the bulk material (see Fig. 6). In practice, thermal design of earth-contact structures is often performed with very little known about local ground conditions and a "representative" thermal conductivity is necessarily assumed.

However, a variety of circumstances can lead to changes in the ground water regime near buildings. For example:

1. precipitation — depending on local conditions (cover/slope, etc.) some rainfall is lost as runoff and some will percolate into the ground, changing the water content of the soil;
2. evaporation — severe drying and possible shrinkage cracking of soils can occur depending primarily on temperature and wind speed;
3. transpiration — soil moisture deficit can be caused by vegetation demands;
4. alteration to existing vegetation — removal of established trees can change local ground water content profile quite significantly;
5. construction/demolition/ground works;
6. ground water abstraction for potable or industrial supply;
7. changes in ground water level — natural or anthropogenic;
8. buried services — the presence of water supply systems, sewerage networks, distributed heating systems, etc. will all have some affect on ground water conditions.

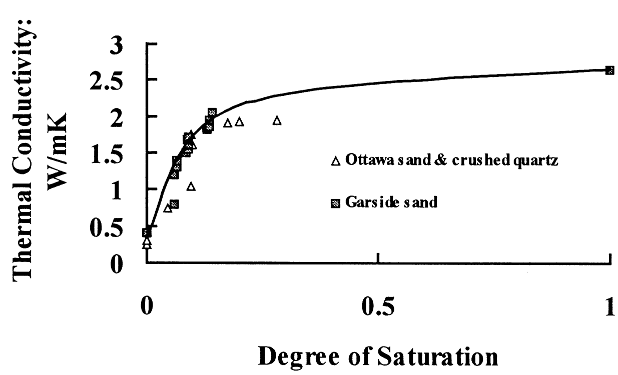

Fig. 6. Thermal conductivity as a function degree of saturation (Ewen and Thomas [180]).

The occurrence of such phenomena may lead directly to a change in the thermal conductivity of the ground beneath or adjacent to a building and can therefore be expected to have some contribution to the ground heat transfer processes that occur. However, the extent to which heat transfer analyses should attempt to include any of these features is debatable and clearly case-specific. As a minimum requirement, a ground thermal conductivity representing average conditions is needed. This of course assumes that "average" conditions can be reasonably assessed.

In order to establish a more comprehensive framework for evaluating such phenomena, the nature of the transport processes that occur needs consideration. In the first instance, ground water flow may occur under saturated conditions, unsaturated conditions or both. In some cases the changes in ground moisture content may be closely coupled to temperature variations, suggesting a coupled solution procedure.

First, considering the effects of saturated conditions. In these circumstances, the bulk soil thermal conductivity will be at its highest — a saturated soil will conduct heat at a faster rate than the unsaturated material. If the ground water is static, then attention need only be placed on obtaining a reasonable estimate of bulk soil thermal conductivity and standard design procedures may suffice. However, in some cases reasonably high flow rates may occur which have the potential to create a heat sink — with heat being transferred from the source into the water course and dissipated at some distance from the structure. However, many soils are of very low permeability, ground water flow rates are low and the ability of the water to "convect" heat from a structure in this manner will be limited.

Some work has been carried out in this general area. For example, the effect of ground water flow has been considered by Hagentoft [65,66] and Delsante [100]. Delsante considered the effect of changing water table depth and temperature on the total heat flux through a slab-on-ground floor. A two-dimensional explicit solution (obtained using a conformal transformation method) was presented. It was concluded that for any water depth greater than the building width, the heat flux was within 10% of the flux calculated in the absence of a water table. However, in this work, the thermal conductivity of the ground above the water table was assumed to be uniform and equal to that of the floor slab. Hagentoft reached very similar conclusions although a different approach was adopted. Hagentoft's work was based on numerical analyses that took into account the ground water flow rate, the permeability of the soil, and insulation over the slab.

Notwithstanding the importance of the saturated condition, the ground beneath and adjacent to many earth-contact structures is likely to be unsaturated much of the time. The region of soil that lies between the water table and the soil surface is referred to as the unsaturated zone. In this region the soil moisture content is dictated by capillary and gravitational forces, in addition to the usual influence of climatic boundary conditions. The soil in this region may therefore include a significant air phase and its degree of saturation will vary with depth — increasing to approximately 100% at the water table. As indicated above, any increase in the

proportion of air in the void space of a soil can be expected to have a significant effect on its overall (or bulk) thermal conductivity. However, analysis of the moisture transfer in the near surface zone will require solution of an unsaturated flow equation — which in turn will require the determination (or estimation) of a number of hydraulic properties of the soil as discussed below.

The manner in which soil moisture content variation is linked to ground heat transfer depends on the extent to which coupling of the heat and moisture migration processes is of importance and the extent to which such information could be incorporated into a subsequent thermal design. In many cases a lack of knowledge of field conditions will be a limiting factor.

In the first instance, an uncoupled approach can be considered. However, even at this relatively simple level, a knowledge of the variation in soil moisture content with depth and time is needed. In the UK, for example, the Meteorological Office provide data on Soil Moisture Deficit which can be used to estimate average changes in ground moisture content. It is then possible to feed such information into a heat conduction analysis utilising a depth varying soil thermal conductivity, determined as a function of soil water content. A more rigorous approach may involve the solution of a coupled set of heat and moisture transfer equations and inclusion of full multi-dimensional effects.

In either case, an understanding of the moisture migration process in unsaturated soils is required. Therefore, the following sections of the review set out the basic concepts needed in this respect. The problem of ground water flow independent of thermal gradients (Isothermal Flow) is first considered. The various methods of estimating the key hydraulic properties which govern moisture migration are then considered. Emphasis is placed on methods of estimation as opposed to methods of measurement. Finally, a brief account of the theoretical background to some established approaches for coupled heat and moisture migration is presented.

7.1. Isothermal moisture transfer

The simplest and most obvious mechanism inducing liquid transport is liquid water flow due to a potential gradient. In unsaturated media this mechanism will cause flow to occur from a zone of greater potential to a zone of lesser potential. The Buckingham–Darcy law [101] states that:

$$\bar{v}_l = -k_l \nabla \Phi \tag{36}$$

where $\bar{v}_l$ is the liquid velocity, k_l is unsaturated hydraulic conductivity and Φ is the total potential for flow.

The total potential is made up from contributions of several smaller potentials. The three most relevant of these were defined by Yong and Warkentin [101] as follows.

1. The capillary (or matric) potential, i.e. the work required per unit distance to transfer a unit quantity of soil solution from a reference pool at the same

elevation and temperature as the soil, to a point in the soil, i.e.

$$\psi_{\mathrm{c}} = \frac{u_{\mathrm{w}} - u_{\mathrm{a}}}{\gamma_{\mathrm{w}}} \tag{37}$$

where u_{w} is the pore water pressure, u_{a} is the air pressure and γ_{w} is the unit weight of water.

2. The gravitational potential, i.e. the work required per unit distance to transfer water from the reference elevation to the soil elevation. The gravitational potential may be given as:

$$\psi_{\mathrm{g}} = -\rho_{\mathrm{l}} g h \tag{38}$$

where g is the acceleration due to gravity, h is the height from the reference elevation and ρ_{l} is the unit mass of water.

3. The osmotic potential, is the work required per unit distance to transfer water from a reference pool of pure water to a pool of soil solution at the same elevation, temperature, etc.

$$\psi_{\mathrm{o}} = n_{\mathrm{salt}} R_{\mathrm{g}} T c_{\mathrm{salt}} \tag{39}$$

where n_{salt} is the number of molecules per mole of salt, R_{g} is the universal gas constant (J kg^{-1} K^{-1}), T is the absolute temperature and c_{salt} is the concentration of salt.

Osmotic gradients found in wet field soils generally account for little water movement [102]. However, in soils exhibiting suctions above 0.5 MPa, these gradients can account for a more significant contribution to liquid transfer. Also, it is obvious that larger gradients, and thus moisture movement, will occur in the vicinity of concentrated solutes.

In most mathematical formulations for liquid transfer it is usually the case that, for simplicity and because of its magnitude, the osmotic potential is neglected and the total potential is assumed to be equal to the sum of the capillary and gravitational potentials.

Having defined the flow velocity, conservation of mass yields a governing equation for moisture transfer. The resulting equation can be written in terms of different primary variables. Two established forms exist. The first is to cast the equations in terms of potential for flow (Richards [103]):

$$C_{\mathrm{l}} \frac{\partial \psi_{\mathrm{c}}}{\partial t} = \nabla(k_{\mathrm{l}} \nabla \psi_{\mathrm{c}}) + \frac{\partial k_{\mathrm{l}}}{\partial z} \tag{40}$$

Here, the equation is solved for capillary potential, ψ_{c}. k_{l} is the hydraulic conductivity and C_{l} is the specific moisture capacity. Both parameters are strongly dependent on the water content of the soil. More detail is provided on the determination of these parameters in the sections that follow.

The alternative is to express the equation in terms of volumetric moisture content:

$$\frac{\partial \theta}{\partial t} = \nabla(D_\theta \nabla \theta) + \frac{\partial k_1}{\partial z} \tag{41}$$

In this case, D_θ is the isothermal moisture diffusivity, which can be related to the specific moisture capacity and the hydraulic conductivity via the following relationship:

$$D_\theta = k_1/C_1 \tag{42}$$

Richards' equation is the most flexible form of the flow equation. It can correctly accommodate layered materials and is compatible with current trends in the analysis of the mechanical behaviour of unsaturated soils [104]. However, for single materials, and in the absence of deformation effects, the diffusivity based equation is attractive because it is numerically stable and also because volumetric moisture content is a more readily understood variable in many disciplines. The limitations of the moisture content based approach are further expounded below in the section on coupled heat and moisture transfer.

7.2. Hydraulic properties of soils

In saturated soil mechanics it is usual to refer to the hydraulic characteristics of a soil in terms of its permeability (SI units m/s). Typical values of permeability, as shown in Table 10, can be found in standard soil mechanics texts (e.g. Scott [105]). In general, a single value is often used to represent the saturated state of the soil. However, heterogeneity and other factors can cause significant variations in permeability even within a fully saturated soil.

The hydraulic response of an unsaturated soil is more difficult to define. It is clear that a single value of "permeability" is not adequate to describe unsaturated flow. Of prime significance is the fact that the ability of a soil to transmit water is strongly dependent on its water content. In order to give recognition to this fact, and in order to help identify the problem as "unsaturated", the term *hydraulic conductivity* is used in place of permeability. Furthermore, when the soil is in an unsaturated state, there is a capacity for the amount of water stored within the pore space to change. This aspect of the hydraulic response of an unsaturated soil is described via the use of the *specific moisture capacity*. This parameter is also highly non-linear (strongly dependent on soil moisture content).

Table 10
Saturated permeability (Scott [105])

Soil type	Permeability, k_1 (m/s)
Gravel	$k_1 > 10^{-2}$
Clean sand	$10^{-2} > k_1 > 10^{-5}$
Silt	$10^{-5} > k_1 > 10^{-8}$
Fissured clay	$10^{-4} > k_1 > 10^{-8}$
Intact clay	$k_1 < 10^{-8}$

As seen above, it is also common to pose the unsaturated flow equations in terms of the total potential gradient causing water to move within the pore space. For many problems the total potential is adequately considered to be the sum of the capillary and gravitational potential. The capillary potential is akin to the hydraulic head in saturated flow problems and the relation between it and the soil moisture content defines the specific moisture capacity of the soil. This relationship is often referred to as the *soil water retention curve* (*or characteristic*).

7.3. Unsaturated hydraulic conductivity

This subject has been the attention of much research, as a result the number of possible approaches are too numerous to be fully explored here. However, an attempt is made to illustrate some of the more widely accepted approaches. Due to its highly non-linear nature and a number of practical difficulties associated with the direct measurement of this parameter, it is common practice to use some form of indirect calculation method [106].

One common theme in the determination of this parameter is the use of the soil water retention curve, which is more easily measured, to define the pore size distribution in the soil. Various techniques can be applied to relate this distribution to the hydraulic conductivity at various degrees of saturation. It is still quite common practice to measure the saturated hydraulic conductivity and then use one of the following techniques to estimate the "unsaturated" variation of this parameter.

Fluid flow through soils finer than coarse gravel can be assumed to be laminar. Recognising this fact, equations have been developed that relate the hydraulic conductivity, k_l, to properties of the soil and permeating fluid. Mitchell [107] stated the following relation:

$$k_l = C_s \frac{\gamma_p}{\mu} \frac{1}{S_0^2} \left(\frac{e^3}{1+e} \right) S_l^3 \tag{43}$$

where C_s is the shape coefficient, γ_p is the unit weight of the permeant, μ is the viscosity of the fluid, S_0 is the wetted surface per unit volume of particles, e is the void ratio and S_l is the degree of saturation.

Eq. (43) becomes the well known Kozeny–Carman equation for the permeability of porous media when $S_l = 1$. The equation predicts that hydraulic conductivity should vary as the cube of the degree of saturation. This relationship has been found reasonable for compacted fine-grained soils and a degree of saturation greater than about 80% [107].

Other equations have been proposed for the hydraulic conductivity of unsaturated soils. Marshall [108] derived the following equation for hydraulic conductivity as a function of pore sizes for an isotropic material:

$$k_l = \eta^2 \frac{[r_1^2 + 3r_2^2 + \cdots + (2n-1)r_n^2]}{8n^2} \tag{44}$$

where n is the total number of sub-divisions of the pore size range, r_i is the mean radius of the pores in a single sub-division i and η is the soil porosity.

The radius of the water-filled pore under a suction is given by:

$$r = \frac{2\sigma_t}{\rho_w g \psi_c} \tag{45}$$

where σ_t is the surface tension of water and ψ_c is the capillary potential.

Eq. (44) can then be rewritten as:

$$k_l = \frac{\sigma^2 \eta^2}{2\rho_w^2 g^2 n^2}[\psi_1^{-2} + 3\psi_2^{-2} + \cdots + (2n-1)\psi_n^{-2}] \tag{46}$$

Marshall took η as equal to the volumetric water content in Eq. (46). Brooks and Corey [109] provided further detail on the application of this method.

Gardner [110] presented a hydraulic conductivity relationship of the following form:

$$k_l = \frac{k_s}{1 + a\left\{\frac{(u_a - u_w)}{\rho_w g}\right\}^n} \tag{47}$$

where a and n are curve-fitting constants, u_a is the pore air pressure and u_w is the pore water pressure.

A further expression for hydraulic conductivity [111] can be written in the form:

$$k_l = \frac{\gamma_l k k_{rl}}{\mu_l} \tag{48}$$

where k is the intrinsic permeability of the soil, k_{rl} is the relative liquid phase coefficient of permeability and μ_l is the dynamic viscosity of the liquid. The relative liquid phase coefficient of permeability was defined by Bear and Verriujt [112] as:

$$k_{rl} = \frac{k_l(S_l)}{k_l\,|_{S_l=1}} \tag{49}$$

where S_l is the degree of saturation of liquid water (i.e. the volume of water divided by the volume of void space in the soil; $0 \le S_l \le 1$).

The dynamic viscosity of liquid water, employed in the above relationships, is known to be strongly dependent on temperature. Kaye and Laby [113] provide the following relationship, which is applicable over the temperature range 0–100°C:

$$\mu_l(T) = 661.2(T - 229)^{-1.562} \times 10^{-3} \tag{50}$$

Alonso et al. [114] have found the following equation to adequately represent the unsaturated hydraulic conductivity of a number of soils:

$$k_{\mathrm{l}} = A\left[\frac{S_{\mathrm{l}} - S_{\mathrm{lr}}}{1 - S_{\mathrm{lr}}}\right]^{\alpha_{\mathrm{l}}} 10^{\alpha e} \tag{51}$$

where e is the void ratio, S_{l} is the degree of saturation, A and α are constants and S_{lr} is the residual degree of saturation.

Even from the brief outline above, it is clear that there are numerous equations available for the calculation of unsaturated hydraulic conductivity. Some further expressions are provided in Table 11. Some arise from curve fitting of experimental data and are therefore not suitable for general application. It is impracticable to attempt to describe the background to the determination of each expression in this review. However, a general description of the parameters involved can be found by reference to the nomenclature list.

Some typical measured hydraulic conductivity data are presented in Fig. 7. The magnitude of hydraulic conductivity is greatest at saturation and can reduce by orders of magnitude as a soil dries. Soil type also dictates the overall hydraulic conductivity with intact clays exhibiting the smallest conductivities.

7.4. Water retention characteristics

Although this relationship is more readily determined than the hydraulic conductivity, there have been a number of attempts to provide theoretical and empirical functions [114,136–139]. Some of these functions were specifically

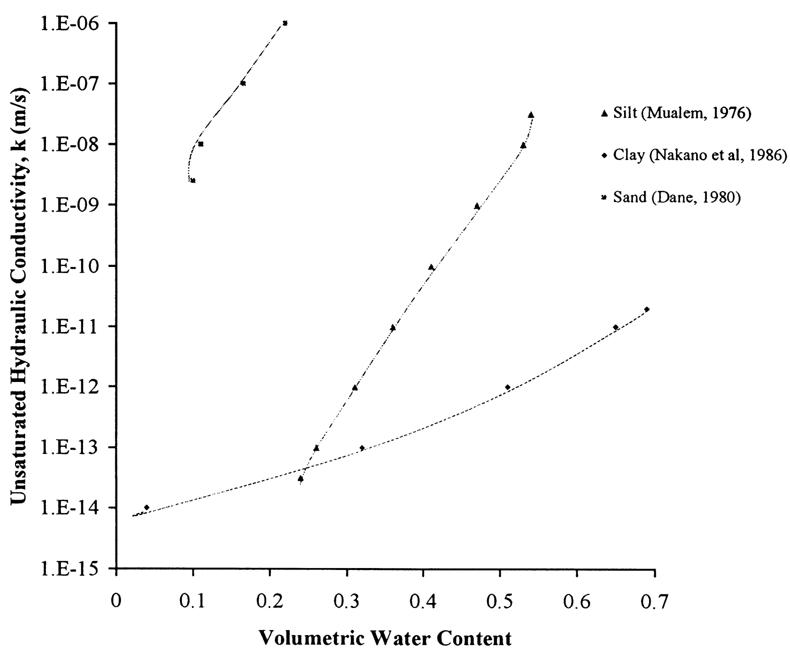

Fig. 7. Typical hydraulic conductivity — water content relationships (Refs. [133–135]).

Table 11
Unsaturated hydraulic conductivity functions

Function	Source	
$k_w = a\psi + b$		Richards [103]
$k_w = a\psi^{-b}$		Wind [115]
$k_w = k_s[1 + a\psi^{-b}]^{-1}$		Gardner [110]
$k_w = k_s \exp[-b\psi]$		
$k_w = k_s$	$\psi_b \leq \psi$	Christensen [116]
$k_w = k_s \exp[a(\psi_b - \psi)]$	$\psi < \psi_b \leq \psi_r$	Rijtema [117]
$k_w = k_r(\psi_b/\psi_r)^{-n}$		Philip [118]
$k_w = k_s$	$\psi_b \leq \psi$	Brooks and Corey [109]
$k_w = k_s(\psi_b/\psi)^m$	$\psi_b > \psi$	
$k_w = k_s[1 + (\psi/\psi)^n]^{-1}$		Arbhabhirama and Kridakorn [119]
$k_w = k_s((S_r - S_{ru})/(1 - S_{ru}))^3$		Imray [120]
$k_w = k_s((S_r - S_{ru})/(1 - S_{ru}))^4$		Corey [121]
$k_w = a\theta_w^b$		Gardner [110]
$k_w = k_s(1 - n(1 - S_r))$		Scott [122]
$k_w = k_s S_r^n$		Brutsaert [123]
$k_w = k_s \exp[b(\theta_w - \theta_s)]$		Davidson et al. [124], Dane and Klute [125]
$k_w = k_s(\theta_w/\theta_s)^{2b+3}$		Campbell [126]
$b = \Delta \log \psi / \Delta \log \theta_w$		Ahuja [127,128], Gillham et al. [129], Zachmann et al. [130], Hillel [131]
$k_w \approx k_s((S_r - S_{ru})/(1 - S_{ru}))^{3.5}$		Kovacs [132]
$k_w = k_s S_e^n[1 - (1 - S_e^{1/m})^m]^2$		Nielsen et al. [102]

developed to be used in the subsequent calculation of the hydraulic conductivity relationship [109,139–143].

Several attempts have been made to derive the water retention curves based on the models of pore radius distribution [142,144]. Pore radius was studied on the basis of soil structure for the purposes of analysing the moisture characteristic as early as 1966 [145]. A statistical distribution equation is normally used to describe the distribution of pore radius. Examples include the incomplete Gamma distribution and the lognormal distribution [143–147]. Kosugi [144] and Fredlund and Xing [143] made use of a distribution curve to derive water retention functions on the basis of the definition of a relation between pore radius and capillary potential (or suction).

In determining expressions to represent the water retention characteristic of a soil, advantage is often taken of distinct features of the shape of the curve. One common feature is referred to as the "air entry value" or the bubbling pressure. This refers to the capillary potential (or suction) value that corresponds to the point at which the soil first becomes unsaturated — soils are able to sustain low values of suction without desaturating. Another feature is the residual (or irreducible) moisture content. This refers to the fact that experimental results often suggest the existence of a minimum moisture content. Beyond this point, any further rise in suction apparently causes no further reduction in moisture content.

Brooks and Corey [109] suggested a water retention model that is frequently used by soil scientists and hydrologists. According to their model, the effective saturation, S_e, is expressed as a power function of ψ_c, the capillary potential:

$$S_e = \left(\frac{\psi_{cB}}{\psi_c}\right)^{\delta} \quad \psi_c \leq \psi_{cB}$$

$$S_e = 1 \quad \psi_c \geq \psi_{cB} \tag{52}$$

where ψ_{cB} is the air entry value. Milly [148] pointed out that the presence of a distinct bubbling pressure and the absence of an inflection point on the suggested retention curve causes discrepancies with field-measured moisture characteristics.

An alternative S-shaped model was proposed by van Genuchten [140,141] in the form:

$$S_e = \frac{1}{(1 + (\alpha \mid \psi \mid)^n)^m} \tag{53}$$

where α and n ($n \geq 1$) represent empirical parameters that are related to the inverse of the bubbling pressure and the pore size distribution index, respectively, and m is related to n by $m = 1-1/n$. This model has an inflection point and performs better than Brooks and Corey's model for many soils, particularly for data near saturation [102].

Russo [142] suggested a model that reproduces Gardner's [110] exponential

model for the water conductivity-capillary potential relationship when incorporated into Mualem's [135] model for relative hydraulic conductivity. Russo's model is:

$$S_e = \left\{ \left(1 + \frac{\alpha \mid \psi \mid}{2}\right) \exp\left(- \frac{\alpha \mid \psi \mid}{2}\right) \right\}^{\frac{2}{2+m}} \tag{54}$$

When $m = 0$, Eq. (54) is identical to a retention model suggested by Tani [149].

Kosugi [144] presented a water retention model by applying a three-parameter log-normal distribution law to the pore radius distribution function and to the water capacity function:

$$S_e = \frac{1}{2}\mathrm{erfc}\left(\frac{\ln\left\{ \dfrac{\psi_{cB} - \psi_c}{\psi_{cB} - \psi_{ci}} \right\} - \sigma^2}{\sqrt{2}\sigma} \right) \quad \psi_c \le \psi_{cB}$$

$$S_e = 1 \quad \psi_c \ge \psi_{cB} \tag{55}$$

where erfc denotes the complementary error function, ψ_{cB} is the bubbling pressure, ψ_{ci} is the capillary pressure at inflection point and σ is a dimensionless parameter. Kosugi compared the calculated results of previous models and his model and found they perform equally well.

Fredlund and Xing [143] proposed an equation also based on the pore-size distribution:

$$\theta = \theta_s \left[\frac{1}{\ln\left[e + \left(\dfrac{\psi_c}{a} \right)^n \right]} \right]^m \tag{56}$$

where θ is the volumetric water content.

Some typical measured water retention data are shown in Figs. 8 and 9. Data obtained for a number of soil types are shown. Fig. 9 illustrates the hysteresis phenomenon that results during wetting/drying cycles. This feature of the water retention curve is most prominent during first time wetting/drying. After repeated wetting/drying cycles a closed hysteresis loop is often formed. Some further empirical water retention relationships are summarised in Table 12.

7.5. Theoretical considerations for coupled heat and moisture transfer in soils

Possibly the first documented attempt to combine thermal effects into the theory of isothermal moisture transfer, in such a medium, was reported in 1943 by Edlefsen and Andersen [156]. Their comprehensive study was arrived at by applying the principle of thermodynamics to the retention and movement of water in a soil system. Application of non-equilibrium or irreversible thermodynamics to

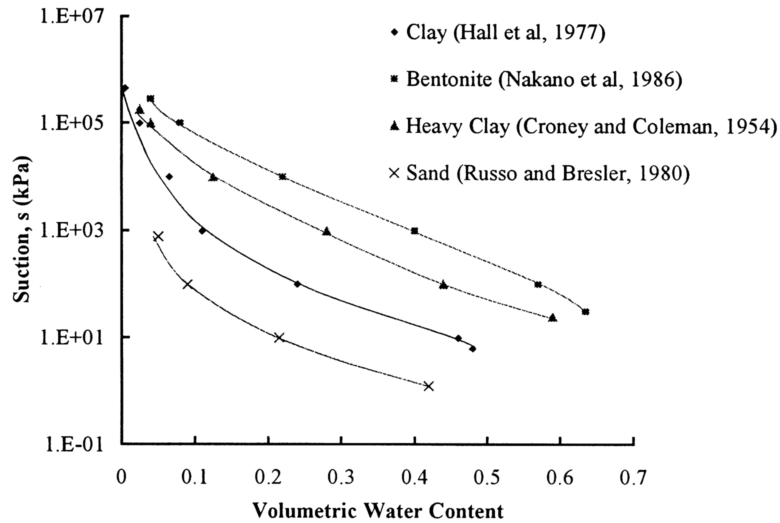

Fig. 8. Typical water retention curves (Refs. [134,150–152]).

the problem continued for some time [157–165]. However, due to practical issues related to parameter determination, a clear preference for an alternative "mechanistic" approach evolved. Therefore, only this latter approach will be described in this review.

Smith [166], Jones and Kohnke [167], Jennings et al. [168] and Gurr et al. [169] were among the first to experimentally observe the influence of thermal effects on the magnitude of the associated moisture redistribution in unsaturated soils. Moisture transfer, particularly in soils at intermediate moisture contents, was seen to be far more significant than had previously been advocated. These observations served to promote research into the field of thermally-induced moisture transfer in unsaturated media.

As with isothermal moisture flow, coupled formulations can be found which are either cast in terms of volumetric moisture content or in terms of potential. The limitations discussed earlier also apply within coupled theories.

Table 12
Water characteristic curves

Function	Source
$\theta = 1/(1 + a\psi^{b})$	Gardner [110]
$\theta = [1/(1 + (\alpha\psi)^{n})]^{m}$	Van Genuchten [140]
$\ln \psi = a + b \ln \theta$	Williams et al. [153]
$\theta = \exp[-(\psi - a)/b]$	McKee and Bumb [154]
$\theta = \{1/\ln[e + (\psi/a)^{n}]\}^{m}$	Fredlund and Xing [143]
$\psi = \psi_{cr} \exp[b(1-\theta)]$	Farrel and Larson [155]

One of the most successful and widely referenced pieces of research carried out to date was presented by Philip and De Vries [170]. Whilst a number of extensions and recommendations to this original study have subsequently been made, including several by De Vries [171], it remains one of the foundation works for heat and moisture transfer in unsaturated soils. A theoretical framework was established that described moisture and heat transfer under combined moisture content and temperature gradients. The equation for the velocity of liquid may be written as:

$$v_l = -D_{\mathrm{Tliq}}\nabla T - D_{\theta\mathrm{liq}}\nabla\theta - k_l i \tag{57}$$

where D_{Tliq} is the thermal liquid diffusivity, $D_{\theta\mathrm{liq}}$ is the isothermal liquid diffusivity, θ is the volumetric water content, k_l the hydraulic conductivity, and i is a unit vector in the z-direction. The simple theory for vapour transfer [172–175], modified so as to apply to porous media, i.e. the inclusion of a tortuosity factor,

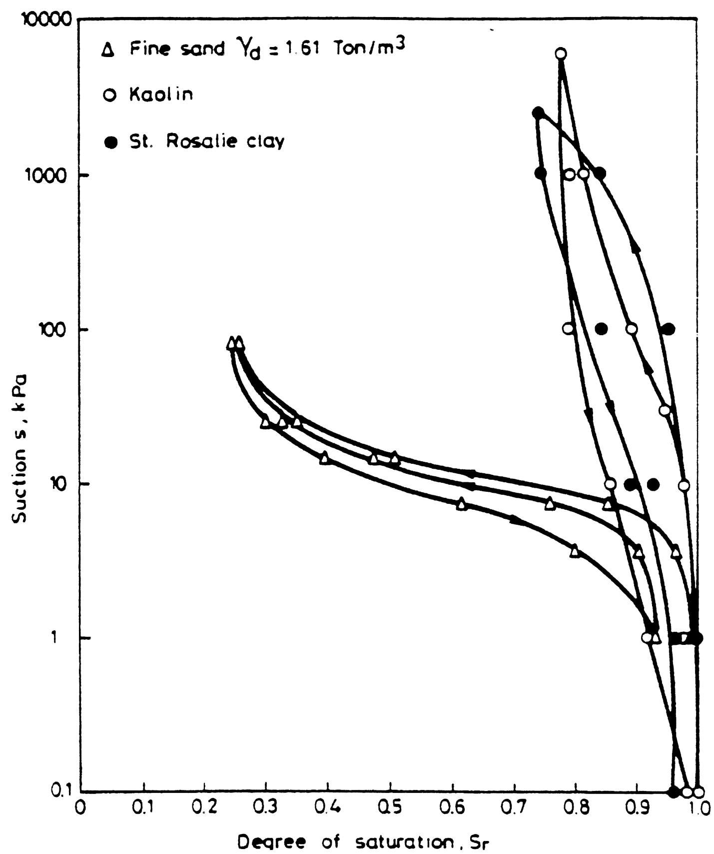

Fig. 9. Further water retention curves (Alonso et al. [114]).

α, the volumetric air content, a, and the "mass-flow" factor, v, was employed by Philip and De Vries.

In relatively dry soils, that often exist in arid regions, moisture transfer in the vapour phase becomes relatively more significant. The total change in the volume of liquid water present in the soil, resulting from this process, is likely to be quite small and in many ground heat transfer problems this component may be neglected. However, to maintain generality, the vapour phase was included in Philip and De Vries' work.

The primary transfer mechanism in the vapour phase is the process of vapour diffusion resulting from thermally-induced vapour concentration gradients. The simple theory for vapour diffusion may be written as:

$$\bar{v}_{\mathrm{v}} = -\frac{1}{\rho_{\mathrm{l}}} D_{\mathrm{atm}} \bar{\Phi} \nabla \rho_{\mathrm{v}} \tag{58}$$

where D_{atm} is the molecular diffusivity of water vapour in air, $\bar{\Phi}$ is a dimensionless coefficient accounting for porosity and extra path length around soil particles, ρ_{l} is the density of liquid water and ρ_{v} is the vapour concentration.

Philip and De Vries' study concludes by presenting a system of two governing equations. The equation governing the moisture transfer is given by:

$$\frac{\partial \theta}{\partial T} = \nabla(D_{\mathrm{T}} \nabla T) + \nabla(D_{\theta} \nabla \theta) + Ki \tag{59}$$

where D_{T} is the thermal diffusivity and D_{θ} is the mass diffusivity. Both terms combine liquid and vapour components.

The equation governing the heat flow through the porous medium is given by:

$$c\frac{\partial T}{\partial t} = \nabla(\lambda + L\epsilon\rho_{\mathrm{l}} D_{\mathrm{T}})\nabla T + \nabla(L\epsilon\rho_{\mathrm{l}} D_{\theta})\nabla\theta_{\mathrm{l}} + L_0\rho_{\mathrm{l}}\frac{\partial(\epsilon K)}{\partial z} \tag{60}$$

where c is the heat capacity, λ the thermal conductivity, L_0 the latent heat of vaporisation, and ϵ the phase conversion factor ($\epsilon = 1$ when moisture transfer occurs in the form of vapour alone, $\epsilon = 0$ when only liquid movement occurs).

De Vries [171] proposed several improvements to the study, carried out in conjunction with Philip [170] a year earlier. Firstly, the author recognised the need to distinguish between the volumetric liquid content, θ_{l}, and the volumetric vapour content, θ_{v}. Furthermore, as a result of this, the possibility of water transfer from the liquid phase to the vapour phase, and vice versa, required the introduction of an evaporation term, E, in the mass continuity equation.

Prior to 1978, virtually every research study adopting the mechanistic phase interaction approach, in the field of heat and moisture transfer in porous media, made use of volumetric moisture content, or volumetric liquid content, and temperature, as the dependent variables. This selection of variables, however, presented severe limitations regarding the types of problem such a formulation could solve. Firstly, the preservation of continuity in passing from unsaturated to saturated soil conditions could not be met. The second limitation, not recognised

when dealing with single-material problems, is that values of volumetric moisture content are generally discontinuous at boundaries between dissimilar soils. Solving such a problem, using a volumetric moisture content formulation, would create a false moisture gradient at the interface, which would induce flows across this boundary, thus invalidating the results. Pressure potential, on the other hand, is continuous across such boundaries and was therefore adopted in a number of subsequent studies.

Sophocleous [176,177] first attempted to modify and extend the form of the equations derived by Philip and De Vries, in order to make them more suitable to general engineering problems. Milly [148] expanded on the approach proposed by Sophocleous by redressing the mechanistic equations for heat and moisture transfer and writing them in terms of capillary potential and temperature. The effect of the heat of wetting, on the resulting moisture flow, is included in the formulation. The model also accounts for the complications of hysteresis present in virtually every soil, and soil heterogeneity. Furthermore, the author recognised the need to incorporate conduction, convection and latent heat of vaporisation effects into the governing heat transfer equation, thus arriving at a comprehensive formulation. The coefficients embedded in these governing equations are generally similar to those described by Philip and De Vries [170,171] only written in alternate form, i.e. capillary potential instead of volumetric moisture content.

Thomas and King [178] proposed a new model considering coupled temperature and capillary potential variations in unsaturated soil. This work resulted in a similar set of differential equations, with some improvements to the treatment of vapour flow, to those presented above, only now cast in terms of potential. Moisture transfer is represented by:

$$C_{\psi\psi}\frac{\partial\psi}{\partial t} + C_{\psi\mathrm{T}}\frac{\partial T}{\partial t} = \nabla(K_{\psi\psi}\nabla\psi) + \nabla(K_{\psi\mathrm{T}}\nabla T) + \frac{\partial k_{\mathrm{l}}}{\partial z} \tag{61}$$

and the corresponding heat transfer equation was presented in the form:

$$C_{\mathrm{T}\psi}\frac{\partial\psi}{\partial t} + C_{\mathrm{TT}}\frac{\partial T}{\partial t} = \frac{1}{\rho_{\mathrm{l}}}\nabla(\lambda\nabla T) - C_{\rho_{\mathrm{l}}}\nabla(Tv_{\mathrm{l}}) - C_{\rho_{\mathrm{v}}}\nabla(Tv_{\mathrm{v}}) - L_0\nabla(v_{\mathrm{v}}) \tag{62}$$

The lumped coefficients on the left hand side of Eq. (61) and (62) relate to liquid and heat storage and are fully defined in the original work [178]. The work has been extended further recently by Thomas and Sansom [179] to provide a comprehensive framework of heat, moisture and air flow in an unsaturated soil.

Within the context of the thermal design for earth-contact buildings, it is the author's view that a formulation of this level of sophistication will only be warranted within the context of research and development. However, application of this type of approach may yield useful insights into ground heat transfer that may aid the design processes in the future. It is worth noting that this type of formulation can readily accommodate a variation of thermal conductivity with moisture content. Empirical data used to establish this relation can be found in the literature [180] (shown previously in Fig. 6).

In the author's view, for the type of problem in hand, the link between moisture content variations and soil thermal conductivity is perhaps the most important "coupling" process. It is possible to include this effect in an indirect (uncoupled) manner by simply modifying the soil thermal conductivity according to its water content. A simple evaluation of this approach will appear in the literature this year [181].

However, fully coupled heat and moisture transfer algorithms also include the influence of temperature variations on moisture content. Cross-coupling in this direction is likely to be of secondary interest for this class of problem. One further issue arises, and that is related to the need to include vapour transport in the moisture transfer equation. Although it is clearly important to include this process in some problems, its value within the content of the energy efficiency of earth-contact structures is not clear at present.

Due to the complexity of coupled formulations, numerical techniques are invariably required to obtain a solution. The reader is directed towards some of the many references available for further information in this respect [e.g. 90,111,181–188].

8. Summary and conclusions

A review of ground heat transfer effects on the thermal performance of earth-contact structures has been presented. An outline of the fundamental heat transfer processes relevant to the problem is provided along with a description of methods of determining appropriate thermal properties of the materials concerned. A summary of the historical developments in analytical, semi-analytical and numerical methods has been presented along with a brief overview of the relevant design guides. A number of techniques for the calculation of the thermal conductivity of a soil have also been considered.

It is clear that analytical methods can provide fast and efficient means of performing calculations in certain circumstances. However, they suffer from some limitations due to the simplifications and assumptions which are generally needed to achieve a solution. This can be seen, for example, in the configuration of slabs considered or with regard to assumptions made in relation to semi-infinite geometry.

Often analytical techniques consider only uninsulated elements. Taking into account internal or external insulation (which requires inclusion of additional materials and possibly more boundary data) then causes extra difficulties. Furthermore, analytical methods often treat ambient conditions in such a way that only constant internal air temperature and sinusoidal time varying external air temperatures are used. In some situations this may be unacceptable to the analyst. Krarti's method seems to be one of the most flexible approaches since it allows the inclusion of various insulation layers and also deals with a range of configurations (slab-on-ground and basements).

As opposed to analytical methods, numerical methods allow greater flexibility.

Numerical simulations can represent: (i) almost any geometrical configuration; (ii) transient or steady-state conditions; (iii) heat flux or temperature boundaries (constant or time varying); (iv) user defined initial conditions; (v) multi-dimensional effects; and (vi) a variety of different material properties. Of course, as a consequence of increased sophistication, potentially prohibitive computer run-times and reduced operability arises.

Numerical models generally use either finite difference or finite element techniques (or some combination of both). Each method has its advantages and disadvantages. Perhaps the most significant aspects relate to the balance between the relatively fast solution times offered by the finite difference method and flexibility offered by the finite element method, in terms of its ability to easily accommodate irregular geometry, etc. The more sophisticated models often remain within the realm of research and development.

The advantages (speed) and disadvantages (potentially too inflexible and simple) of analytical methods as noted in previous sections also apply to simplified methods and design guides. As earth-contact heat transfer involves many parameters pertinent to each case (e.g. climatic data, thermophysical properties, geometric configuration, insulation, etc.), the limitations of such guides must be evaluated for the problem in hand. This area of work appears worthy of further investigation.

Amongst the group of design guides available, the new European Standard appears to be the most detailed and flexible. However, the ASHRAE method is the most widely used, although there are potential problems associated with summer basement predictions using this method. Whilst the CIBSE method is limited to floors, the French AICVF method is more generally applicable. These guides remain critically important in practice as they define thermal requirements in construction.

Considering multi-dimensional heat transfer, a number of investigations have been performed that suggest quite large errors in heat flux calculation can occur when naturally three-dimensional problems are subject to geometric simplification. Similar problems exist when two-dimensional results are compared to one-dimensional calculations. This effect is clearly problem dependent, but nevertheless needs further clarification with regard to its implications on design calculations.

It is clear that the thermal properties of soils may vary with temperature and moisture content, amongst other factors. In recognition of this, a considerable amount of the review has been dedicated to providing a background to the effects of moisture content changes on ground heat transfer. In particular, the more general case of unsaturated soils has been considered. An account of the methods available, to determine the relevant hydraulic properties of a soil, has also been presented.

The need to include full non-linearity of parameters and coupling between moisture and heat transfer processes appears worthy of further investigation. However, current indications suggest that this type of analysis will only be required in a relatively small number of cases. As an intermediate step, thermal conduction analysis of a ground heat transfer problem can be performed utilising

a knowledge of field water content variations in the determination of soil thermal conductivity.

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